



Future changes in heatwaves characteristics in Romania

Bogdan Antonescu^{1,2,3} · Dragoş Ene^{1,4} · Mihai Boldeanu^{1,5} · Simona Andrei¹ · Luminiţa Mărmureanu^{1,6} · Cristina Marin^{1,7} · Răzvan Pîrloagă^{1,3}

Received: 22 September 2022 / Accepted: 21 February 2023 / Published online: 23 May 2023
© The Author(s) 2023

Abstract

The changes in the characteristics of heatwaves over Romania have been analyzed using the excess heat factor calculated for two climate change scenarios (RCP4.5 and RCP8.5) from the EURO-CORDEX project. The changes were evaluated for the near future (2021–2050) using the historical period (1971–2000) as reference. The frequency of occurrence and the duration of heatwaves is projected to increase for both climate scenarios in particular over southern Romania. In this region, the percentage of change in the near future for the number of heatwaves is between 50 and 60% for the RCP4.5 scenario and 60–80% for the RCP8.5 scenario. Also for the same region, the duration of heatwaves will increase by 30–50% for the RCP4.5 scenario and 60–80% for the RCP8.5 scenario. These results indicate that the human exposure to heatwaves will increase in Romania in the near future. To increase awareness on heatwaves and their impact, we propose a series of immediate actions that include (1) improving the communication of the impact of heatwaves, (2) identification of the regions where the population is more vulnerable to heatwaves, and (3) better understanding of the mortality and morbidity associate with heatwaves in Romania.

Keywords Heatwaves · Climate changes · Near future · Excess heat factor · Romania

1 Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicated that the frequency of occurrence and intensity of hot temperature extremes has increased over the recent period and will further increase (Masson–Delmotte et al. 2021a). As indicated in the IPCC report, globally a hot temperature extreme event over land (including heatwaves) occurred on average once in 10 years during the pre-industrial period (1850–1900). Currently, for an increase with approximately 1.1°C of the mean global temperature, these events occur on average three times in 10 years and are 1.2°C hotter (Masson–Delmotte et al. 2021b, FigureSMP.6). These changes in the characteristics of hot temperature extreme events already lead to an increase in the mortality associated with them. For example, Vicedo-Cabrera et al. (2021) using data collected from 43 countries between 1991 and 2018 showed that climate change has increased the mortality associated with hot temperature extreme events by 37%. Other studies indicated that

the impact of these events, in particular heatwaves, will significantly increase in the future (e.g., Forzieri et al. 2017).

In the past decades, Europe has experienced a series of high-impact heatwaves. One of the most significant heatwaves that affected Europe occurred in 2003 and resulted in more than 70,000 fatalities (Robine et al. 2008). This was followed by the heatwave that affected south-eastern Europe in 2007 and resulted in losses exceeding €2 billion and 19,000 people being admitted to hospitals in Romania only (Founda and Giannakopoulos 2009; Mircheva et al. 2017; Demirtas 2018). Other outstanding events occurred in the decade 2010–2019. Over eastern Europe a heatwave that occurred in 2010 was associated with 55,000 deaths and economic losses estimated at €11 billion (Dole et al. 2011; Barriopedro et al. 2011; Schneidereit et al. 2012). Major agricultural losses in Bosnia and Herzegovina, Serbia, and Italy were associated with a heatwave that affected southern Europe in 2017 (Kew et al. 2019). In 2018 a heatwave that occurred over southwestern, central, and northern Europe nearly doubled the daily mortality in Portugal (Barriopedro et al. 2020) and lead to unprecedented forest fires in Scandinavia (Yiou et al. 2020).

Given the current and future increases in the frequency of occurrence and intensity of heatwaves, it is important to study

✉ Bogdan Antonescu
antonescu.bogdan@gmail.ro

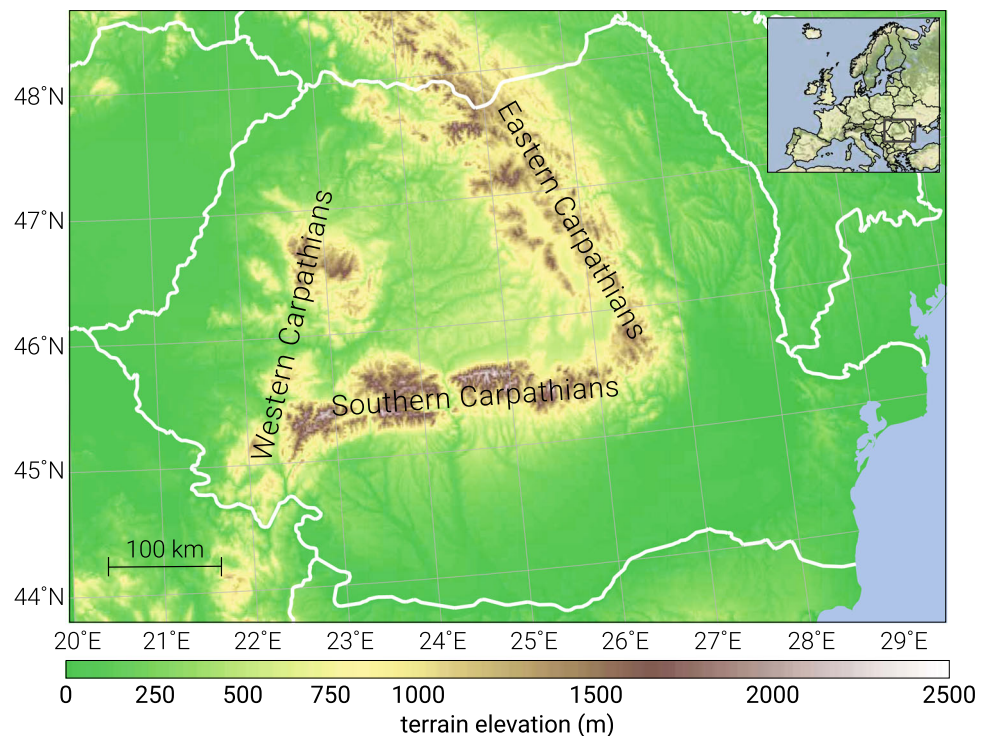
Extended author information available on the last page of the article

these events from a regional perspective and to assess their impact on population, ecosystems and local infrastructure. This can lead to the development of adaptations strategies and improvement of early warning systems to reduce the impact of heatwaves (e.g., Lowe et al. 2011). Due to its geographical position, Romania is affected by heatwaves that occur over central, south-eastern and eastern Europe (Fig. 1). Heatwaves that occurred in Romania between 1983 and 2012 were analyzed by Barbu et al. (2014) using data from weather stations. In their study, the Romanian territory was divided into four regions and a heatwave was defined as a period of at least three days during which the maximum daily temperature was greater than the 90th percentile (using the 1961–1990 as reference period) for a specific region. The threshold was 33°C over the eastern, intra-Carpathian and western regions, and 35°C for southern Romania. Their results showed that 2144 heatwaves recorded at 105 weather stations occurred during the study period. Also, they indicated that the main synoptic-scale systems responsible for the onset of heatwaves in Romania are the ridges that envelopes southern Europe advecting tropical air masses from northern Africa. Sfică et al. (2017) also studied the heatwaves (i.e., an event that occurred between May and September) and warm spells (i.e., an event that occurred between October and April) in Romania. The events were identified based on daily maximum temperature recorded at 27 weather stations between 1961 and 2015 using the 90th percentile as a temperature threshold and a minimum period of three consecutive days. Thus, 111 heatwaves and warm spells that hit simultaneously were

identified (representing a total of 423 days). Sfică et al. (2017) also noted an increase in the number of heatwave days during the last 15 years of the study period. Nagavciuc et al. (2022) studied the spatial and temporal variability and the trends of hot and dry summers in Romania between 1950 and 2020. They defined a heatwave based on 90th percentile of the daily maximum temperature (using a 15 days window centered on each calendar day) and having a duration of at least 5 consecutive days. Their results showed that the length, spatial extent and frequency of heatwaves increased in Romania during the study period for all summer months with the rate of increase accelerated after the 1990s. Thus, the smallest number of heatwaves during the study period was observed between 1970 and 1985 and the highest number between 2001 and 2020. Other studies on heatwaves in Romania, focused on their characteristics from a regional perspective. For example, Bocancea (2018) studied the frequency of occurrence of heatwaves in the area of Iași, a city in northeastern Romania. Between 1961 and 2016, based on data from meteorological stations, 98 heatwaves (defined using the 95th percentile of maximum daily temperature) occurred in Iași. The majority of heatwaves had a duration of 3 (41.7%) or 4 days (35.4%).

Very few studies have analyzed the societal and economic impact of heatwaves in Romania. For Cluj–Napoca, a large city in northwestern Romania, Herbel et al. (2018) analyzed the impact of heatwaves on urban heat island and the local economy for the summer of 2015. For the three events analyzed, the economic losses in Cluj–Napoca were estimated at €2.5 million per heatwave day (a total of €38 million for

Fig. 1 Topography of Romania (terrain elevation shaded according to the scale). The inset map indicates the position of Romania within Europe. Topography data obtained from NOAA National Geophysical Data Center (2022)



the events analyzed). Vicedo-Cabrera et al. (2021) estimated that the mortality associated with hot temperature extreme events in Romania has increased by 25.2% during the study period 1991–2018. For the eight cities included in the analysis, the number of fatalities attributed to human-induced climate change varied from 9 to 18 fatalities per year except for Bucharest (i.e., 103 fatalities per year).

Given the current impact of heatwaves in Romania, which is estimated to rise in the future as the mean global temperature is increasing, the aim of this article is to assess the near future (2021–2050) changes in the characteristics of heatwaves based on data provided by the EURO-CORDEX project (Jacob et al. 2014). Knowing the near future changes in the characteristics of heatwaves could help to develop adaptation measures to reduce the impact of these events. Because there is no consistent definition of heatwaves across Europe, in this article, we use the Excess Heat Factor (EHF, Langlois et al. 2013; Nairn and Fawcett 2015) to analyze the heatwaves characteristics. EHF was introduced as a predictor for high risk of heat-related mortality and morbidity (Langlois et al. 2013). One of the main advantages of using EHF is that it can be applied to any region and does not depend on arbitrary thresholds for temperature or period of the year. Thus, given the complex topography of Romania and the vicinity of the Black Sea, EHF is suitable to be used for the study of heatwaves in this region. EHF was recently used by Piticar et al. (2018) to study the changes in the heatwaves characteristics over Romania based on data from 31 weather stations between 1961 and 2015. Their analysis indicated that heatwaves have become more frequent, more intense and longer in Romania. In this article, we further use EHF to study the future changes in heatwaves characteristics in Romania using climate projection data over the entire territory.

2 Data and methods

2.1 Excess heat factor

The Excess Heat Factor (EHF) incorporates two daily excess heat indices (EHI, Nairn and Fawcett 2015). The first EHI index, the significance index (EHI_{sig}), measures how the average daily mean temperature for three consecutive days compares with the 95th percentile of daily mean temperature (T_{95}).

$$EHI_{sig} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - T_{95} \tag{1}$$

where i represents each day of the study period for a specific location and T_{95} is the 95th percentile for the same location. The second EHI index, the acclimatization index

(EHI_{accl}), compares the average daily mean temperature for three days period with the average daily mean temperature over the recent past defined as a period of 30 days (Nairn and Fawcett 2015).

$$EHI_{accl} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - \frac{T_{i-1} + \dots + T_{i-30}}{30} \tag{2}$$

EHI_{accl} is a measure of the adaptation to high temperatures. If EHI_{accl} is positive, there is a lack of acclimatization and increased potential for adverse effects (i.e., increased mortality or morbidity). These two indices are then combined into EHF

$$EHF_i = EHI_{sig} \cdot \max(1, EHI_{accl}) \tag{3}$$

Thus, a day is a part of a heatwave if for that day EHF_i ($^{\circ}C^2$) is positive, which implies that EHI_{sig} is positive. If the EHI_{accl} is greater than 1, then is acting as an amplifying factor for the EHF_i (Nairn and Fawcett 2015). Given the methodology for EHF, Perkins and Alexander (2013) indicated that this index is more sensitive for determining different aspects of heatwaves than, for example, using the 90th percentile of the daily maximum temperature over a 15-day interval as was previously used. Next we describe the dataset used to calculate EHF over Romania.

2.2 EURO-CORDEX data

The EHF dataset analyzed in this study is based on six different publicly available model simulations and two representative concentration pathway scenarios. The simulations (Table 1) are using a common configuration defined by the EURO-CORDEX initiative (<http://www.euro-cordex.net/>; Jacob et al. 2014), the European branch of the World Climate Research Program Coordinated Regional Downscaling Experiment (CORDEX; <http://wcrp-cordex.ipsl.jussieu.fr/>; Giorgi et al. 2009). The EURO-CORDEX simulations used in this study have a horizontal grid spacing of 0.11° (approximately 12.5 km). The data (i.e., mean daily temperature calculated by averaging minimum and maximum daily temperature) were extracted from Rossby Centre regional climate model (RCA4, Kjellström et al. 2016). Six global climate models (GCMs) provided boundary layer conditions of the RCA4 runs between 1971 and 2050 (Table 1). Two periods were analyzed: the historical period (1971–2000) and the near future period (2021–2050). Two representative concentration pathway scenarios (RCP; Moss et al. 2010) were considered for the period 2021–2050: RCP4.5 (i.e., due to reductions in greenhouse gas emission, the radiative forcing is stabilized at 4.5 W m^{-2} before 2100) and RCP8.5 (i.e., due to increases in the greenhouse gas emissions, the radiative forcing will reach 8.5 W m^{-2} by 2100). Next, we present

Table 1 Overview of the regional climate runs used in the study and their main characteristics

Modelling center	GCM	Member
Centre National de Recherches Météorologiques Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (Voltaire et al. 2013)	CNRM-CM5	r1i1p1
EC-EARTH consortium (Hazeleger et al. 2010)	EC-EARTH	r12i1p1 (RCP4.5) r1i1p1 (RCP8.5)
Institut Pierre-Simon Laplace (Dufresne et al. 2013)	IPSL-CM5A-MR	r1i1p1
Met Office Hadley Centre (Collins et al. 2011)	HadGEM2-ES	r1i1p1
Max Planck Institute for Meteorology (Popke et al. 2013)	MPI-ESM-LR	r1i1p1
Norwegian Climate Centre (Bentsen et al. 2013)	NorESM1-M	r1i1p1

Three scenarios were analyzed for all runs the historical control run encompassing the period 1971–2000, RCP4.5, and RCP8.5 for all runs

the statistical analysis applied to the EHF dataset to retrieve the characteristics of heatwaves in Romania.

2.3 Statistical analysis

A heatwave is defined in this article as a period of at least three consecutive days with positive EHF. Unlike previous studies (e.g., Piticar et al. 2018) that considered heatwaves during the extended summer season (May–September), in this article we have considered heatwaves over the entire year as summer-like temperature will be prolonged in late spring and early summer. Furthermore, recent studies have indicated that summer in mid latitudes of the Northern Hemisphere has lengthened and is projected to last nearly half a year by 2100 (Wang et al. 2021).

EHF was computed for each of the six regional climate runs between 1971 and 2050. The 95th percentile for daily mean temperature used in Eq. 1 was based on the data for the historical period (1971–2000) for each run. Next, only positive values for EHF were selected and the following parameters were calculated for each run: mean annual number of days with positive EHF, mean annual value of positive EHF, mean annual duration of heatwaves, and mean annual number of heatwaves. These parameters were then merged into a single data frame with the mean values from the six runs.

The impact of climate change on heatwaves in Romania was addressed by comparing the RCP4.5 and RCP8.5 climate scenarios (ensemble mean of the six simulations) over the near future (2021–2050) with the historical period (1971–2000). Thus, the mean values (e.g., number of days with positive EHF) for the historical period were subtracted from the mean values resulting from the two climate scenarios. This difference was then used to calculate the percentage

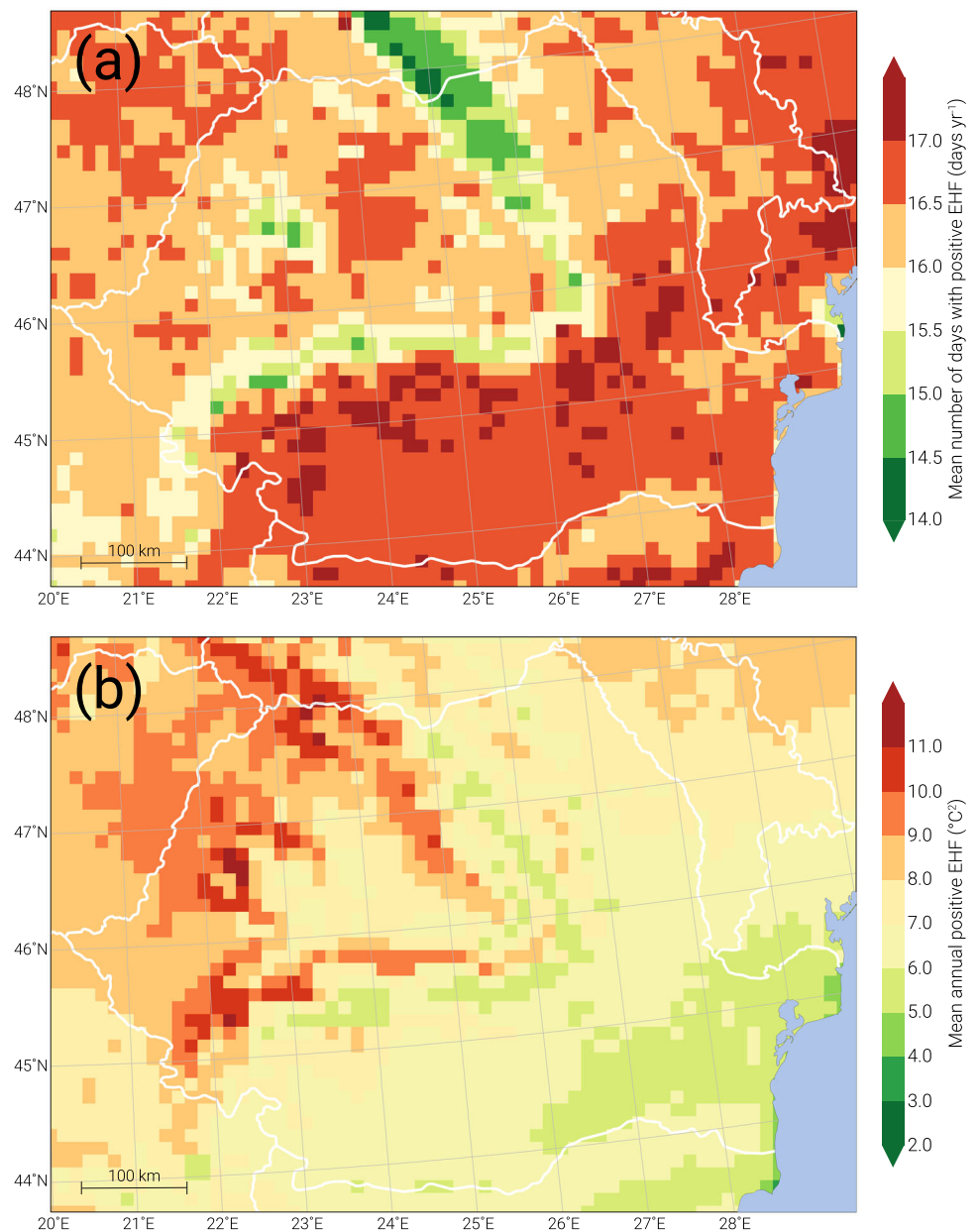
of change for the two climate scenarios compared with the historical period.

A two-sided Wilcoxon rank-sum test was used to distinguish robust ($\alpha = 0.05$) differences from the historical period (Wilcoxon 1945). This test was used in previous papers to evaluate the systematic differences between the distributions of two independent samples (e.g., Lorenzo et al. 2021). To evaluate trends, the nonparametric Theil-Sen slope estimator was used (Sen 1963). Sen's slope unlike the regression slope is insensitive to outliers. Trends were considered statistically significant for each pixel if the p value was less than 0.05 based on the nonparametric Mann-Kendall trend test (Kendall 1975). The advantage of using the classical Mann-Kendall test is that the data are not required to be normally distributed, and also the test is not affected by the length of the time series. The Mann-Kendall test and the Sen's slope were performed using the pyMannKendall package for Python (Hussain and Mahmud 2019).

3 Past characteristics of heatwaves in Romania

During the historical period (1971–2000) high values for the mean annual number of days with positive EHF were observed over the south, southeastern, and parts of central Romania (>16.5 days yr^{-1} , Fig. 2a). A lower number of days with positive EHF occurred over mountain areas, in particular over the eastern Carpathians Mountains (< 15 days yr^{-1}). When days with positive EHF occurred over western and northwestern Romania, they were characterized by higher mean annual values (i.e., $>8^{\circ}\text{C}^2$) compared with the other regions (Fig. 2b). The lowest mean annual values for positive EHF (i.e., $<6^{\circ}\text{C}^2$) were observed over southeastern Romania close to the Black Sea, and over the Carpathians

Fig. 2 (a) Mean annual number of days with positive EHF (days, shaded according to the scale), and (b) mean annual values of positive EHF ($^{\circ}\text{C}^2$, shaded according to the scale) for the period 1971–2020



Mountains (Fig. 2b). The distribution of mean annual positive EHF is modulated by the climatic differences between central Romania (i.e., Intra-Carpathians) influenced by the northern and north-western circulations and sheltered by the Carpathians Mountains. The climate of western Romania is mainly influenced by the Central Europe climate (i.e., continental climate) and southern and southeastern Romania is mainly influenced by the Mediterranean climate. The high values for mean number of days with positive EHF over southern Romania are associated with tropical airmass advectations from north Africa especially during the summer months (Barbu et al. 2014). The mean annual positive EHF ($>6^{\circ}\text{C}^2$) within Intra-Carpathian sub-mountain regions could be attributed to foehn effects (e.g., Apostol and Sfică 2013) determined

by southern and eastern circulations (Fig. 2b). Over the plain region in western Romania the increase in the mean annual values for positive EHF **could also be due** to southwestern circulation from north Africa towards Central Europe. Also, the extension of the North African ridge towards Eastern Europe, allows for a supplemental provision of tropical airmass from the Arabian Peninsula, which can lead to prolonged heatwaves over eastern Romania. These circulations are associated with the typical heatwaves patterns over Europe identified by Felsche et al. (2023). Data between 1981 and 2010 from a 50-member regional climate model were analyzed by Felsche et al. (2023) to derive the main heatwave patterns over Europe using hierarchical agglomerative clustering. The nine patterns obtained correspond

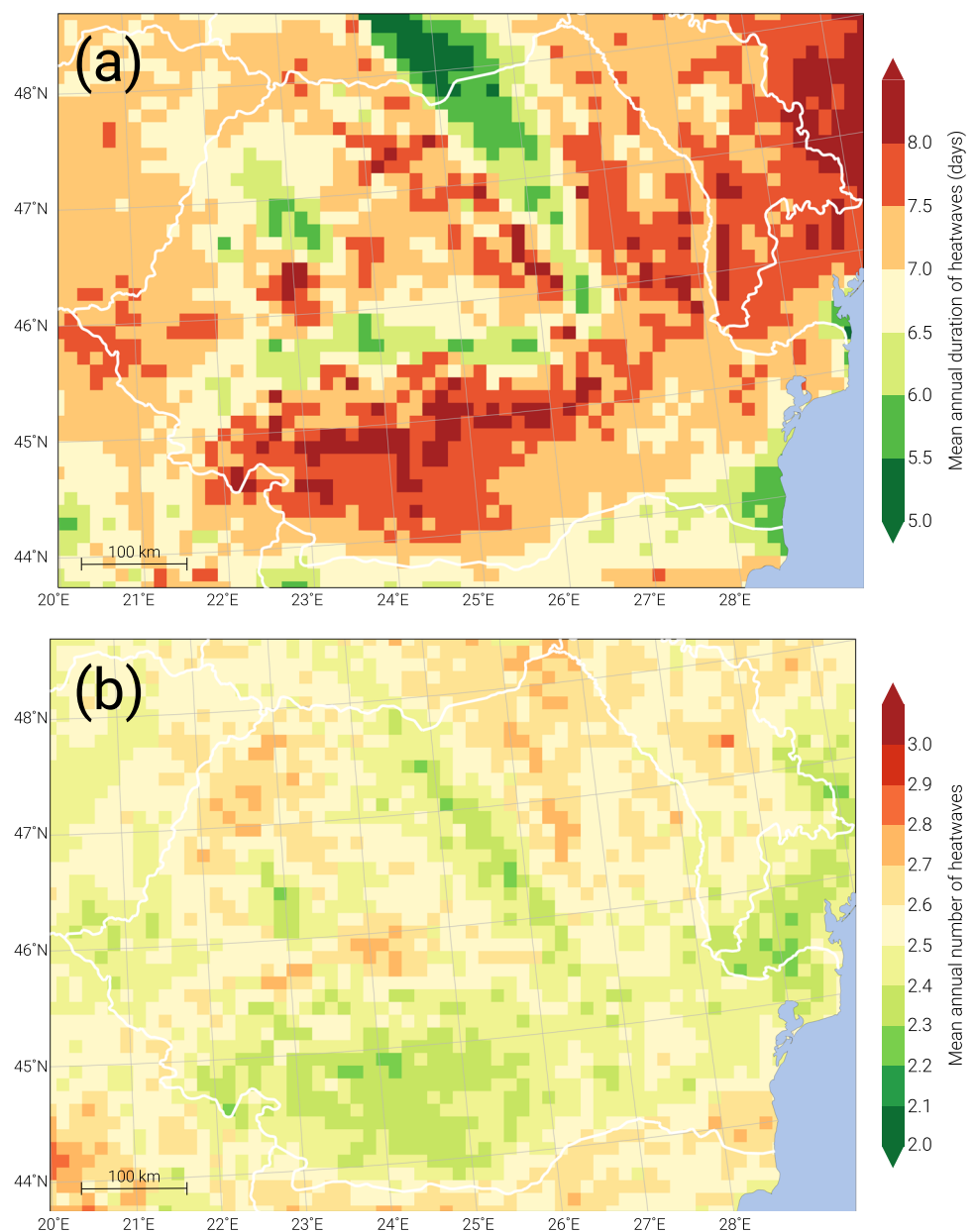
well with those derived from the observational dataset. For Romania, three patterns are relevant: South-Eastern Europe (influencing the entire Romania, in particular western Romania), North-Eastern Europe (influencing eastern Romania), and Greece and Italy (influencing southern Romania) pattern.

Low values ($<6^{\circ}\text{C}^2$) for the mean annual positive EHF are observed close to the Black Sea and over the southeastern Romania (Fig. 2b). By comparison, the results obtained for Iberian Peninsula by Lorenzo et al. (2021), using a similar dataset to the one used in this article, showed that high values of EHF were characteristic for the western Iberian Peninsula and Cantabrian mountain range, and low values for the Mediterranean coastal areas.

Heatwaves (i.e., ≥ 3 consecutive days with positive EHF) that occurred over parts of southern, eastern Romania, and parts of the Intra-Carpathian region had a longer mean annual duration (>7.5 days) compared with other regions (Fig. 3a). The mean annual number of heatwaves varied from 2.2–2.5 over southern Romania to 2.6–2.8 over northeastern Romania and parts of the Intra-Carpathian region (Fig. 3b). Heatwaves over northwestern Romania were as frequent as those from the northeastern part (i.e., 2.6–2.8, Fig. 3b) but they were characterized by shorter duration (<7 days yr^{-1} , Fig. 3a) and higher EHF values (Fig. 2b).

Similar to the results obtained in this article, Piticar et al. (2018) showed that using 1971–2000 as a reference period for the 90th percentile, the mean annual number of heatwaves

Fig. 3 (a) Mean annual duration of heatwaves (days, shaded according to the scale), and (b) mean annual number of heatwaves (shaded according to the scale) for the period 1971–2020



was 2.5 events per year (for the reference periods 1981–2010 the number of events decreased to 1.7). Furthermore, their results indicated the duration of heatwaves was 6.6 days for the reference period 1971–2000 and 5.7 days for 1981–2010.

The number of days with positive EHF had a statistically significant increasing trend over the entire Romania. For most of the country the increase is between 3 and 4 days per decade, except for the northeastern, eastern Romania (in the proximity of the Black Sea) and foothills of southern Romania where is between 4 and 5 days per decade (Fig. 4a). Over the same period, the intensity of heatwaves (i.e., mean EHF values) show a small increase over most of the country but this trend is not statistically significant (Fig. 4b).

The duration of heatwaves has increased during the historical period in particular over southern and southeastern Romania (>1 day decade⁻¹, Fig. 5a). There is also a statistically significant low increase (0.5–1 days decade⁻¹) in the duration of heatwaves over the northwestern part of the country. Concerning the number of heatwaves, there is an increase over eastern Romania (0.25–0.75 heatwaves decade⁻¹) but this trend is not statistically significant over the entire region (Fig. 5b). For the number of heatwaves, Piticar et al. (2018) obtained increasing statistically significant trends (0.64 events per decade using 1971–2000 as reference; 0.52 events per decade using 1981–2010) for $>94\%$ of the stations. Also, their results concerning the

Fig. 4 The trends for (a) the annual mean number of days with positive EHF (days decade⁻¹), and (b) mean annual positive EHF (°C² decade⁻¹) for the period 1971–2020. White dots are plotted where trends are significant at $\alpha = 0.05$

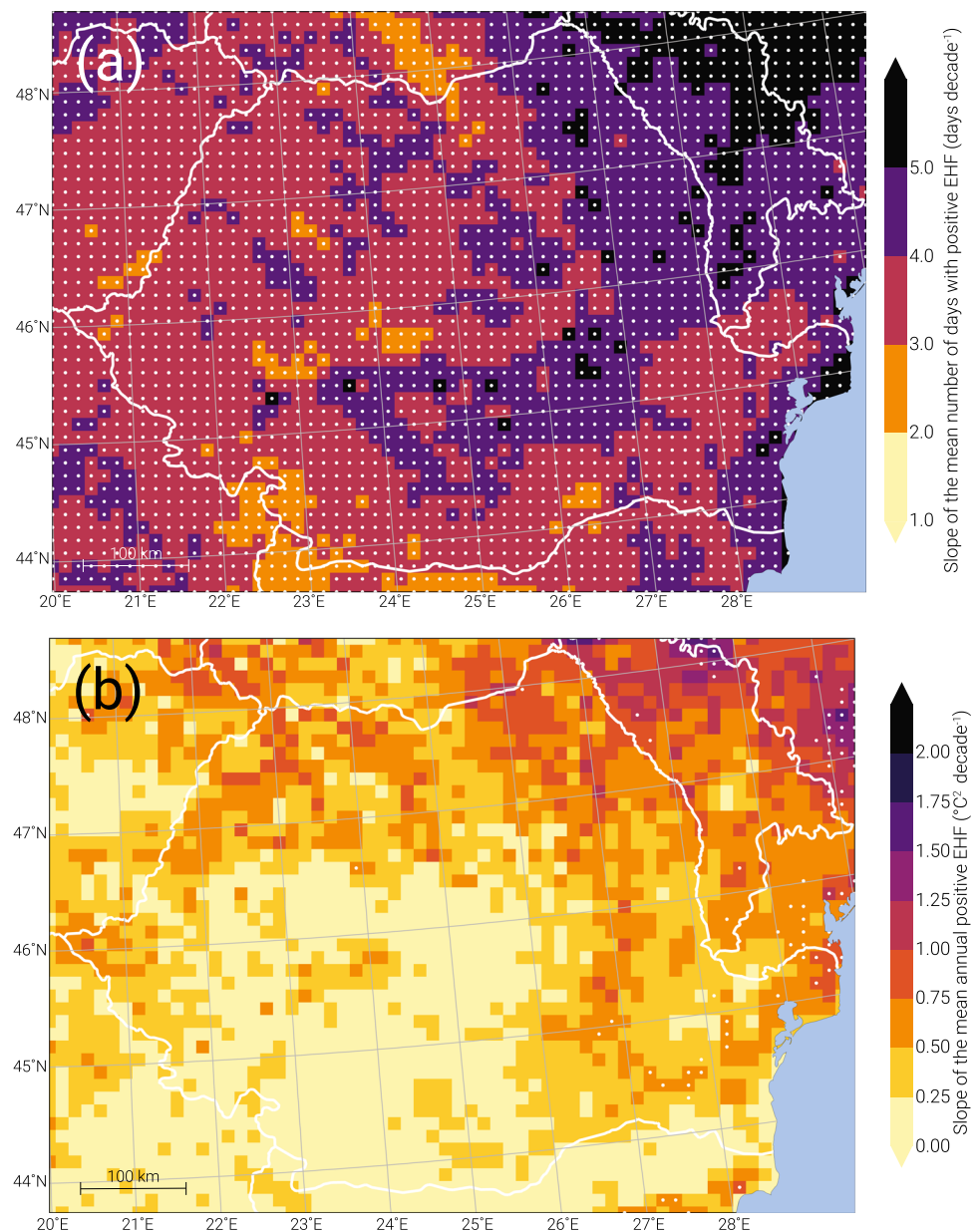
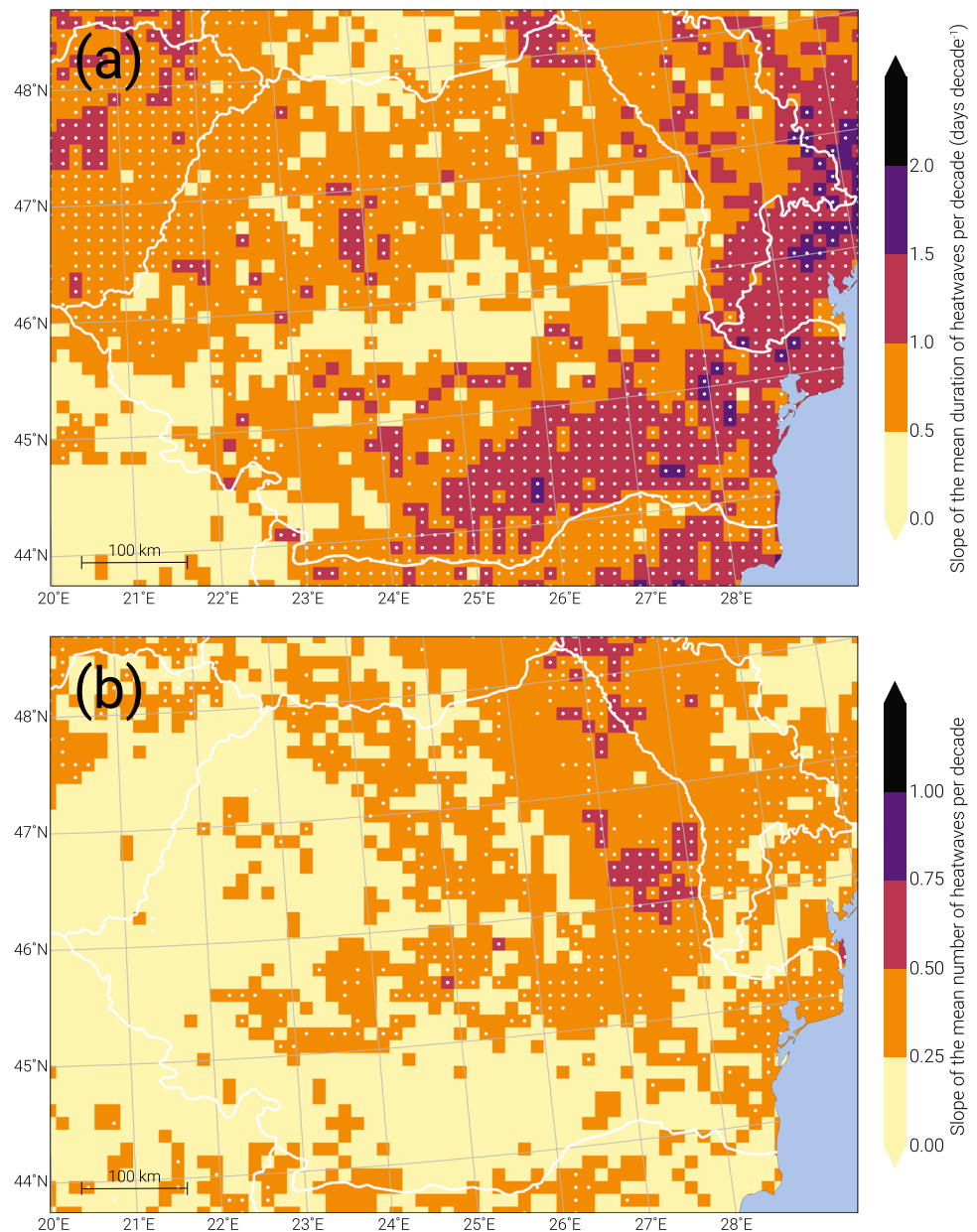


Fig. 5 The trends for (a) mean duration of heatwaves (days decade⁻¹), and (b) number of heatwaves for the period 1971–2020. White dots are plotted where trends are significant at $\alpha = 0.05$



trends in the duration of heatwaves were similar to those obtained here (i.e., 0.84 days per decade for 1971–2000 as reference; 0.62 days per decade using 1981–2010).

4 Near future characteristics of heatwaves in Romania

The percentage of change between the historical period and the near future period is shown in Fig. 6 for the mean number of days with positive EHF and mean annual value of positive EHF. For the RCP4.5 scenario, the increase in the number of days with positive EHF is between 70 and 80% over north-western and northeastern Romania and greater than 100%

over southern Romania and Carpathian Mountains (Fig. 6a). For the RCP8.5 scenario the pattern of change is similar with the one for the RCP4.5 scenario, but the values are greater than 80% over the entire country. The highest percentage of change is also observed for this scenario over southern Romania (i.e., greater than 130%) and Carpathian Mountains (i.e., greater than 150%).

The comparison between the percentage of change in the mean annual value of positive EHF for the two scenarios shows higher values in general for the RCP8.5 scenarios compared with the RCP4.5 scenario (Fig. 6b, d). For the RCP4.5 scenario, the percentage of change is greater than 20% over the entire country except for the region close to the Black Sea (Fig. 6b). Values greater than 30% for the percentage of

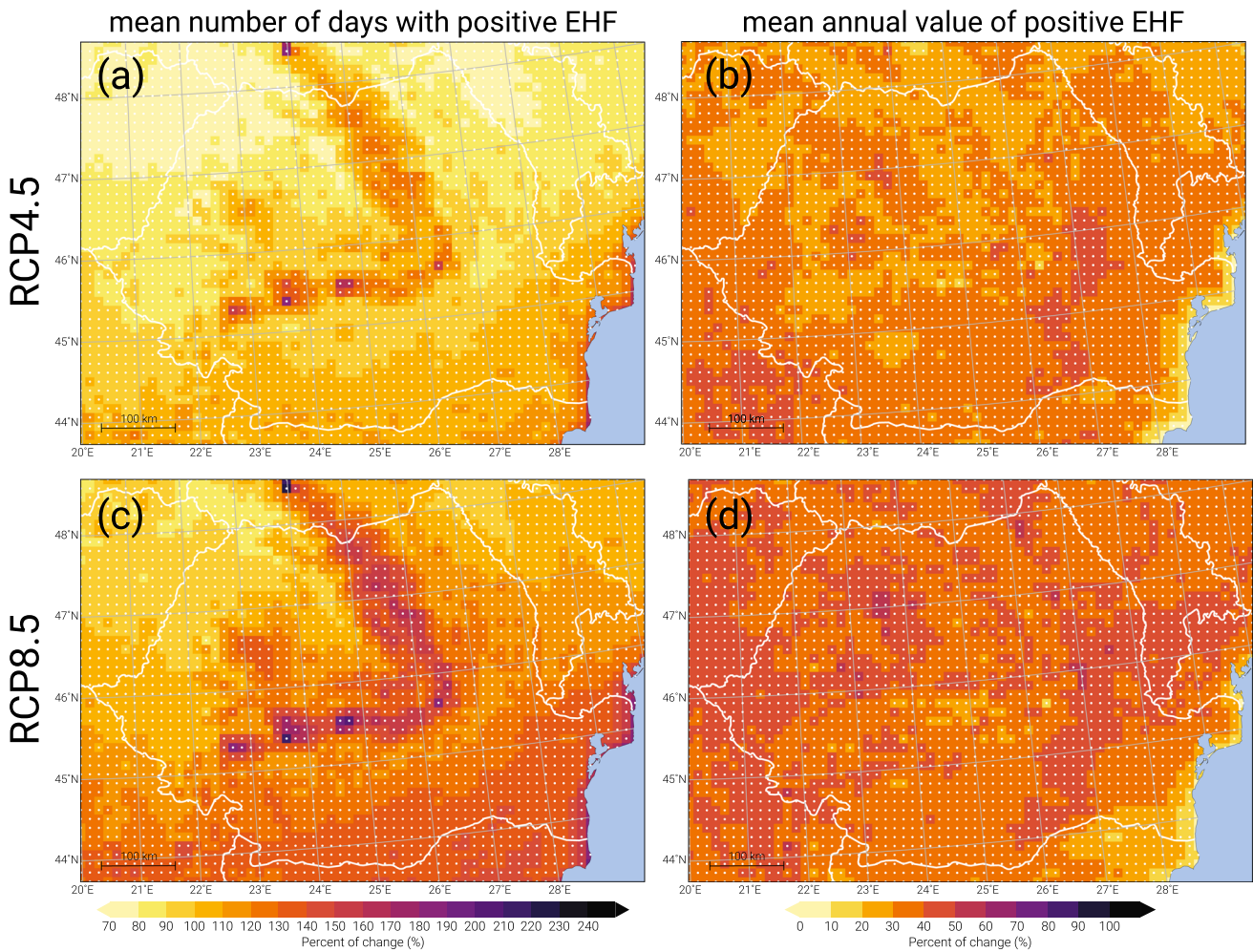


Fig. 6 Percentage of change in projected mean number of days with positive EHF (a, c) and mean annual values of positive EHF (b, d) for the period 2021–2050. White dots represent significant change at $\alpha = 0.05$

change characterize the entire territory except for the region close to the Black Sea and the southern Carpathian Mountains (Fig. 6d). Thus, in the future we can expect an increase in the number of days with positive EHF over southern Romania and higher mean annual values for positive EHF over southeastern and eastern Romania for both scenarios compare with the historical period.

Figure 7 shows the percentage of change for the mean duration of heatwaves and the number of heatwaves between the historical and the near future period for the two climate scenarios. For both scenarios, the mean duration of heatwaves is shown to increase over southern Romania (30–50% for RCP4.5, and 50–70% for RCP8.5, Fig. 7a, c). The highest percentage of change for the mean duration of heatwaves is observed close to the Black Sea coast (>80%). Not only the mean duration of heatwaves shows an increase for the RCP4.5 scenario but also the number of heatwaves is increasing over southern and eastern Romania (50–60%, Fig. 7b). For the RCP8.5 scenario there is a similar increase in the

number of heatwaves (i.e., 50–60%) but over most of Romania (Fig. 7d). Bojariu et al. (2015) also studied the changes in the heatwaves characteristics for the period 2021–2050 compared with 1971–2000 using EURO-CORDEX simulations for the RCP4.5 and RCP8.5 scenarios. The definition used by the Romanian National Meteorological Administration for a heatwave—a period with at least two consecutive days with the maximum temperature $>37^{\circ}\text{C}$ —was used in their study. Similar to the results presented in this article, Bojariu et al. (2015) indicated for the near future (2021–2050) there are no large differences between the two scenarios. Also, their results showed an increase in the number of days of heatwave especially over the southern, southeastern and western Romania. Thus, in the future we can expect more frequent heatwaves with a longer duration especially over southern Romania for both scenarios compared with the historical period. Over the Carpathian mountains there is a strong increase in the number of heatwaves for both scenarios which is expected to have an impact on the tourist activities in this

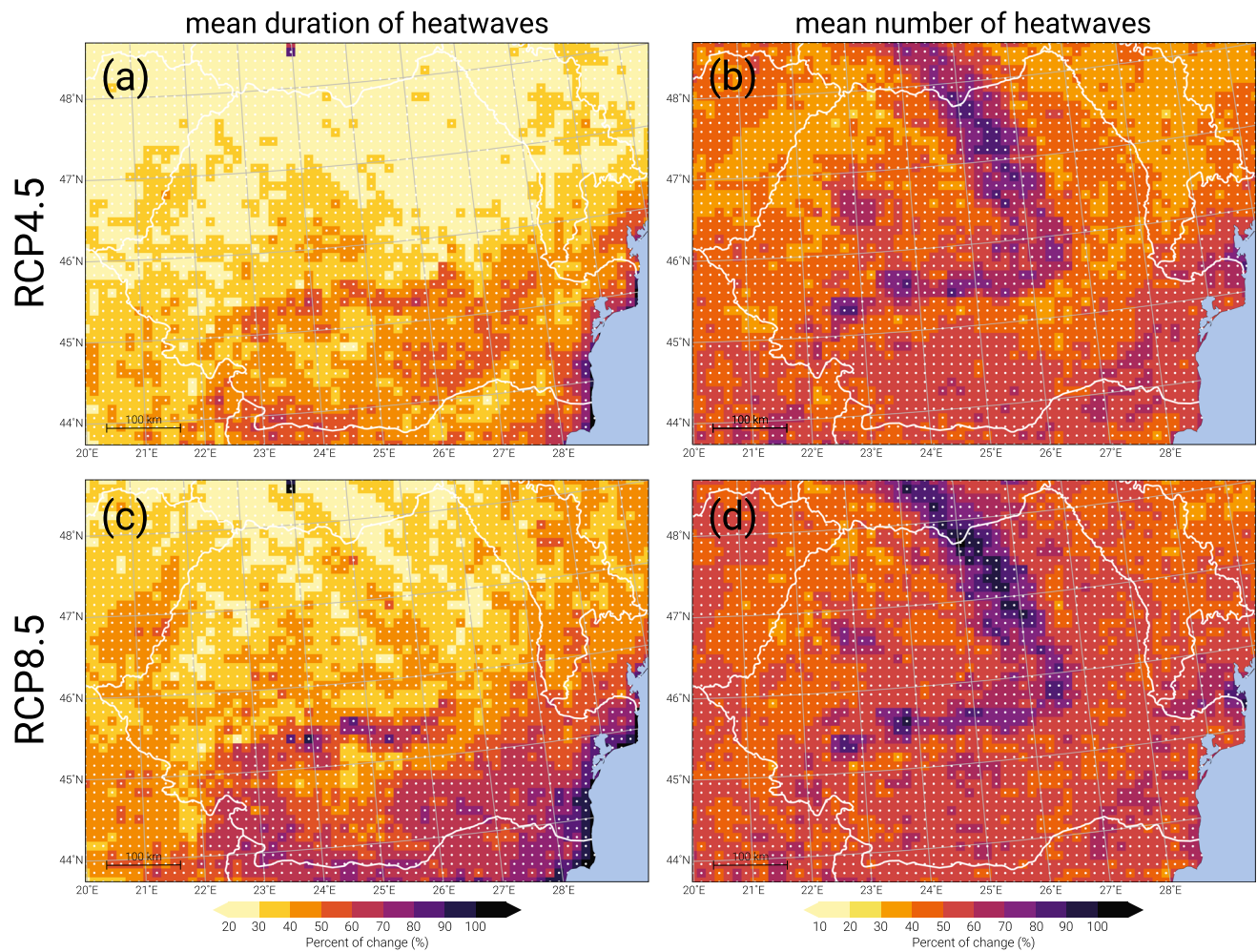


Fig. 7 Percentage of change in projected mean duration of heatwaves (a, c) and mean number of heatwaves (b, d) for the period 2021–2050. White dots represent significant change at $\alpha = 0.05$

area. Another touristic region that will be impacted by heatwaves is the Black Sea region which is expected to have a strong increase in the mean duration of heatwaves.

5 Recommendations to reduce the impact of heatwaves in Romania

The results obtained in this article show that the number and duration of heatwaves will increase in Romania in the near future (2021–2050) compared with the historical period (1971–2000). Given the current impact of heatwaves in Europe these results indicate that this impact will further increase (e.g., mortality). Thus, political and social actions are necessary to reduce the impact of heatwaves and their associated heat stress in Romania, especially over southern parts. Current actions include the warnings issued

by the Romanian National Meteorological Administration for extreme temperature and heatwaves and the recommendations provided by the Ministry of Internal Affairs through the Department for Emergency Situations using the “Be prepared” platform (<https://fiipregatit.ro/ghid/canicula/>, accessed on 8 August 2022). To further reduce the impact of heatwaves in the current and future climate in Romania we propose a series of recommendations.

Implementation of bioclimatologic indices for heat stress that can be used to assess the impact of extreme temperatures and heatwaves on population and can also improve the communication of this impact to the public. For example, Antonescu et al. (2021) have used the Universal Thermal Climate Index (UTCI) (Bröde et al. 2013; Jendritzky et al. 2012) from ERA5–HEAT (Human thErMal comfort) dataset (Di Napoli et al. 2020) to study the changes in thermal stress in Europe between 1979 and 2019. UTCI takes

into account not just the temperature and humidity but also the wind and radiation and is divided in ten thermal stress categories from extreme cold stress to extreme heat stress. The results obtained by Antonescu et al. (2021) indicated that the number of hours with heat stress increased over different regions of Europe including southern part of Romania. Also, Bucharest, the capital city of Romania, was one of the most affected cities by heat stress after Thessaloniki and Rome (the average trend in the number of hours with heat stress was 7.0 hrs yr⁻¹). Besides bioclimatological studies, UTCI can be implemented operationally as was done for Czechia, Italy, Poland, Portugal and also pan-European (Di Napoli et al. 2021). The operational implementation of UTCI along with the existing parameters used to communicate to the public the occurrence of extreme temperature events and heatwaves has the following advantages: (1) UTCI include all the significant parameters (i.e., temperature, humidity, wind, radiation) affecting the human physiological response to the surrounding environment, (2) using the UTCI heat stress categories instead of temperature and humidity thresholds (which can vary from one region to another) can improve the communication to the public of the impact of extreme temperature events and heatwaves, and (3) each UTCI thermal stress category include also a series of protection measures needed to be taken by the population (see Table 2 in Antonescu et al. (2021) for a summary).

Besides improving the communication of the impact of heatwaves, it also important to identify the regions in which the population is more vulnerable to this type of extreme weather events. Unfortunately there is a paucity of research at country level with most of the studies addressing this issue from a local perspective (e.g., Grigorescu et al. 2020; Török et al. 2021). Elderly people, infants, pregnant women, people isolated socially or those suffering from cardiovascular or respiratory disease are the most vulnerable to heatwaves (e.g., Liu et al. 2022). Furthermore, according to Eurostat the median age of the population in Romania will increase from 44.8 in 2025 to 49.6 in 2050 increasing the vulnerability to heatwaves (Eurostat 2023). In Romania, urban population represent currently approximately 54% from the total population (World Bank 2022). For the urban population the vulnerability to heatwaves is exacerbated through the Urban Heat Island (Zhao et al. 2018). Thus, the results obtained in this study for the current and near future characteristics of heatwaves can be used together with studies that identify the area socially vulnerable to heatwaves as basis to develop climate change adaptation plans to these extreme weather events.

Another important aspect of understanding the impact of heatwaves in Romania is the lack of studies, for example, on the mortality and morbidity associated with heatwaves.

Recent studies on mortality associated with extreme temperature events and heatwaves in Romania focused on individual cities. For example, Croitoru et al. (2018) analyzed the impact of extreme temperatures on human mortality for Cluj–Napoca and Scripcă et al. (2022) for the five of the most populated cities of Romania (i.e., București, Cluj–Napoca, Constanța, Iași, and Timișoara). As far as the authors are aware, there are no studies analyzing the impact of heatwaves on mortality and morbidity at national level or at least for the regions most affected by heatwaves in the current and future climate (e.g., southern Romania). These types of studies are essential for developing better policies for reducing the impact of heatwaves.

6 Conclusions

This study assesses the near future changes in the heatwaves characteristics in Romania and thus (1) is filling a gap in our current knowledge concerning this type of extreme weather events in Romania, and (2) is providing a basis for actions to reduce the impact of heatwaves (in particular on human health). The analysis was constructed based on the Excess Heat Factor (EHF) derived from daily EURO-CORDEX data for 1971–2000 (the historical period) and 2021–2050 (the near future period) for two climate scenarios (RCP4.5 and RCP8.5). The main conclusions are:

- For the historical period, south, southeastern and central Romania are characterized by high values for the annual number of days with positive EHF (> 16.5 days yr⁻¹);
- High mean annual values for EHF were observed for western and northwestern Romania (> 8°C²);
- Heatwaves with the longest mean annual duration (> 7.5 days) occurred over parts of southern, eastern Romania, and parts of the Intra-Carpathian;
- Over southern Romania the mean annual number of heatwaves was between 2.2 and 2.5 events. Greater values (2.6–2.8 events) occurred over northeastern Romania and parts of the Intra-Carpathian region;
- The trend in the mean annual number of days with positive EHF showed an increasing statistically significant trend over the entire country (> 3–4 days decade⁻¹);
- A statically significant increasing trend was also observed for the duration of heatwaves (> 1 day decade⁻¹) but only for southern and southeastern Romania;
- For the near future period, the percentage of change in the projected mean annual number of days with positive EHF is greater than 80% over most of the territory for both climate scenarios;

- For the percentage of change in the mean annual values of EHF, values greater than 20% are projected of the entire Romania (with the exception of the region close to the Black Sea) for both climate scenarios;
- The mean duration of heatwaves increased over southern Romania with 30–50% for RCP4.5 scenario and 50–70% for RCP8.5 scenario;
- The mean annual number of heatwaves show a similar increase (>50%) for both scenarios over southern and eastern Romania.

Is expected that in the near future, due to the increase in the frequency of occurrence and duration of heatwaves and also due to the increasing vulnerability of the population, Romania will most likely face an increase in the morbidity and mortality associated with heatwaves. Thus, this article, one of the first in Romania analyzing the future changes in heatwaves characteristics, is emphasizing the urgent need to develop adaptation strategies to reduce the future impact of heatwaves.

Acknowledgements The work for this study was performed through the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. PN 23 05. Further support was provided by the grants of the Romanian Ministry of Education and Research, CNCS-UEFISCDI (Project No. PN-III-P1-1.1-TE-2019-0649) within PNCDI III, Ministry of Research, Innovation and Digitization, CCCDI - UEFISCDI (Project No. PN-III-P2-2.1-PED-2021-1938) within PNCDI III, and by the Romanian Ministry of Research, Innovation and Digitalization, through Program 1- Development of the national research-development system, Subprogram 1.2 - Institutional performance - Projects to finance the excellent RDI, Contract no. 18PFE/30.12.2021. Bogdan Antonescu received partial funding from the project ClimExRo (Grant Agreement: DG-2209-64717) financed by the European Climate Foundation. Dragos Ene acknowledges the ‘EXCELSIOR’: ERATOSTHENES: Excellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment H2020 Widespread Teaming project (www.excelnior2020.eu). The ‘EXCELSIOR’ project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 857510, from the Government of the Republic of Cyprus through the Directorate General for the European Programmes, Coordination and Development and the Cyprus University of Technology. Luminița Mărmureanu was partially funded by Romanian Ministry of Research, Innovation and Digitization, within the core FORCLIMSOC Programme (Contract No. 12N/2023), Project IDs PN 23090101.

Author Contributions Conceptualization, B.A. and D.E.; methodology, B.A., D.E., M.B.; software, D.E. and M.B.; formal analysis, all authors; investigation, all authors; data curation, B.A. and R.P.; writing—original draft preparation, all authors; writing—review and editing, all authors; visualization, D.E. and B.A. All authors have read and agreed to the published version of the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Antonescu B, Mărmureanu L, Vasilescu J et al (2021) A 41-year bioclimatology of thermal stress in Europe. *Int J Climatol* 41:3934–3952. <https://doi.org/10.1002/joc.7051>
- Apostol L (2013) Thermal differentiation induced by the Carpathians Mountains on the Romanian territory. *Carpathian J Earth Environ Sci* 8:215–221. <https://doi.org/10.23937/2469-5858/1510053>
- Barbu N, Georgescu F, Stefanescu V et al (2014) Large-scale mechanisms responsible to heat waves occurrence in Romania. *Rom J Phys* 59:1109–1126
- Barriopedro D, Fischer E, Luterbacher J et al (2011) The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science* 332:220–224. <https://doi.org/10.1126/science.1201224>
- Barriopedro D, Sousa PM, Trigo RM et al (2020) The exceptional Iberian heatwave of summer 2018. *Bulletin of the American Meteorological Society* 101:S29–S34. <https://doi.org/10.1175/BAMS-D-19-0159.1>
- Bentsen M, Bethke I, Debernard JB et al (2013) The Norwegian earth system model, NorESM1-M. Part 1: Description and basic evaluation. *Geosci Model Dev* 6:687–720. <https://doi.org/10.5194/gmd-6-687-2013>
- Bocancea R (2018) Heat waves frequency. A study case of Iași city, Romania (1961–2016). *Geogr Tech* 13:10–19. <https://doi.org/10.1016/j.envres.2020.110268>
- Bojariu R, Bîrsan M, Cică R et al (2015) Schimbările climatice - De la bazele fizice la riscuri și adaptare. Editura Printech, București
- Bröde P, Błażejczyk K, Fiala D et al (2013) The Universal Thermal Climate Index UTCI compared to ergonomics standards for assessing the thermal environment. *Ind Health* 51:16–24. <https://doi.org/10.2486/indhealth.2012-0098>
- Collins WJ, Bellouin N, Doutriaux-Boucher M et al (2011) Development and evaluation of an Earth-System model - HadGEM2. *Geosci Model Dev* 4:1051–1075. <https://doi.org/10.5194/gmd-4-1051-2011>
- Croitoru A, Piticar A, Sfică L et al (2018) Extreme Temperature and Precipitation Events in Romania. *Academiei Române, Bucharest*
- Demirtas M (2018) The high-impact 2007 hot summer over Turkey: atmospheric-blocking and heat-wave episodes. *Meteorol Appl* 25:406–413. <https://doi.org/10.1002/met.1708>
- Di Napoli C, Barnard C, Prudhomme C et al (2020) ERA5-HEAT: a global gridded historical dataset of human thermal comfort indices from climate reanalysis. *Geosci Data J* 8:2–10. <https://doi.org/10.1002/gdj3.102>
- Di Napoli C, Messeri A, Novák J et al (2021) The Universal Thermal Climate Index as an operational forecasting tool of human biometeorological conditions in Europe. In: Krüger EL (ed) *Applications*

- of the Universal Thermal Climate Index UTCI in Biometeorology: Latest Developments and Case Studies. Springer International Publishing, p 193–208. https://doi.org/10.1007/978-3-030-76716-7_10
- Dole R, Hoerling M, Perlwitz J et al (2011) Was there a basis for anticipating the 2010 Russian heat wave? *Geophys Res Lett* 38:L06702. <https://doi.org/10.1029/2010GL046582>
- Dufresne JL, Foujols MA, Denvil S et al (2013) Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Clim Dym* 40:2123–2165
- Eurostat (2023) EUROPOP2019 - Population projections at national level (2019–2100). https://ec.europa.eu/eurostat/databrowser/view/PROJ_19NDBI/default/table?lang=en&category=proj_proj_19n. Accessed 23 Jan 2023
- Felsche E, Bööhnisch A, Ludwig R (2023) Inter-seasonal connection of typical European heatwave patterns to soil moisture. *npj Clim Atmos Sci* 6(1):1–11. <https://doi.org/10.1038/s41612-023-00330-5>
- Forzieri G, Cescatti A, Batista e Silva F et al (2017) Increasing risk over time of weather-related hazards to the European population: a data-driven prognostic study. *Lancet Planet Health* 1:e200–08. [https://doi.org/10.1016/S2542-5196\(17\)30082-7](https://doi.org/10.1016/S2542-5196(17)30082-7)
- Founda G, Giannakopoulos C (2009) The exceptionally hot summer of 2007 in Athens, Greece – A typical summer in the future climate? *Glob Planet Change* 67:227–236. <https://doi.org/10.1016/j.gloplacha.2009.03.013>
- Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: The CORDEX framework. *WMO Bull* 58:175–183
- Grigorescu I, Mocanu I, Mitrică B et al (2020) Socio-economic and environmental vulnerability to heat-related phenomena in Bucharest metropolitan area. *Environ Res* 192:32997965. <https://doi.org/10.1016/j.envres.2020.110268>
- Hazeleger W, Severijns C, Semmler T et al (2010) EC-Earth. *Bull Am Meteorol Soc* 91:1357–1364
- Herbel I, Croitoru A, Rus AV et al (2018) The impact of heat waves on surface urban heat island and local economy in Cluj-Napoca city, Romania. *Theor Appl Climatol* 133:681–695. <https://doi.org/10.1007/s00704-017-2196-4>
- Hussain M, Mahmud I (2019) Pymannkendall: a python package for non parametric mann kendall family of trend tests. *J Open Source Softw* 4(39):1556. <https://doi.org/10.21105/joss.01556>
- Jacob D, Petersen J, Bea Eggert (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg Environ Change* 14:563–578. <https://doi.org/10.1007/s10113-013-0499-2>
- Jendritzky G, de Dear R, Havenith G (2012) UTCI-Why another thermal index? *Int J Biometeor* 56:421–428. <https://doi.org/10.1007/s00484-011-0513-7>
- Kendall M (1975) Rank Correlation Methods. 4th ed. Charles Griffin, 202 pp
- Kew S, Philip S, Oldenborgh G et al (2019) The exceptional summer heat wave in Southern Europe 2017. *Bull Am Meteorol Soc* 100:S49–S53. <https://doi.org/10.1175/BAMS-D-18-0109.1>
- Kjellström E, Barring L, Nikulin G et al (2016) Production and use of regional climate model projections - a swedish perspective on building climate services. *Clim Serv* 2–3:15–29. <https://doi.org/10.1016/j.cliser.2016.06.004>
- Langlois N, Herbst J, Mason K et al (2013) Using the Excess Heat Factor (EHF) to predict the risk of heat related deaths. *J Forensic Leg Med* 20:408–411. <https://doi.org/10.1016/j.jflm.2012.12.005>
- Liu J, Varghese BM, Hansen A et al (2022) Heat exposure and cardiovascular health outcomes: a systematicreview and meta-analysis. *Lancet Planet Health* 6:e484–e495. [https://doi.org/10.1016/S2542-5196\(22\)00117-6](https://doi.org/10.1016/S2542-5196(22)00117-6)
- Lorenzo N, Alejandro D, Royé D (2021) Heatwave intensity on the Iberian Peninsula: Future climate projections. *Atmos Res* 258:105655. <https://doi.org/10.1016/j.atmosres.2021.105655>
- Lowe D, Ebi KL, Forsberg B (2011) Heatwave Early Warning Systems and Adaptation Advice to Reduce Human Health Consequences of Heatwaves. *Int J Environ Res Public Health* 8:4623–4648. <https://doi.org/10.3390/ijerph8124623>
- Masson–Delmotte V, Zhai P, Pirani A et al (eds) (2021a) IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, In Press
- Masson–Delmotte V, Zhai P, Pirani A et al (eds) (2021b) IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, In Press
- Mircheva B, Tsekov M, Meyer U et al (2017) Anomalies of hydrological cycle components during the 2007 heat wave in bulgaria. *J Atmos Sol Terr Phys* 165–166:1–9. <https://doi.org/10.1016/j.jastp.2017.10.005>
- Moss RH et al (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463:747–756. <https://doi.org/10.1038/nature08823>
- Nagavciuc V, Scholz P, Ioniță M (2022) Hotspots for warm and dry summers in Romania. *Nat Hazards Earth Syst Sci* 22(4):1347–1369. <https://doi.org/10.5194/nhess-22-1347-2022>
- Nairn J, Fawcett R (2015) The Excess Heat Factor: a Metric for heatwave intensity and its use in classifying heatwave severity. *Int J Environ Res Public Health* 12:227–253. <https://doi.org/10.3390/ijerph120100227>
- NOAA National Geophysical Data Center (2022) Etopo1 1 arc-minute global relief model. noaa national centers for environmental information. <https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ngdc.mgg.dem:316>. Accessed 9 Aug 2022
- Perkins SE, Alexander LV (2013) On the measurement of heat waves. *J Clim* 26:4500–4517. <https://doi.org/10.1175/JCLI-D-12-00383.1>
- Piticar A, Croitoru AE, Ciupertea FA et al (2018) Recent changes in heat waves and cold waves detected based on excess heat factor and excess cold factor in Romania. *Int J Climatol* 38:1777–1793. <https://doi.org/10.1002/joc.5295>
- Popke D, Stevens B, Voigt A (2013) Climate and climate change in a radiative-convective equilibrium version of ECHAM6. *J Adv Model Earth Syst* 5:1–4. <https://doi.org/10.1029/2012MS000191>
- Robine J, Cheung S, Le Roy S et al (2008) Death toll exceeded 70,000 in Europe during the summerr of 2003. *CR Biol* 331:171–178. <https://doi.org/10.1016/j.crv.2007.12.001>
- Schneiderreit A, Schubert S, Vargin P et al (2012) Large-Scale Flow and the Long-Lasting Blocking High over Russia: Summer 2010. *Mon Wea Rev* 140:2967–2981. <https://doi.org/10.1175/MWR-D-11-00249.1>
- Scripcă A, Acquaforta F, Croitoru A et al (2022) The impact of extreme temperatures on human mortality in the most populated cities of Romania. *Int J Biometeorol* 66:189–199. <https://doi.org/10.1007/s00484-021-02206-w>
- Sen PK (1963) Estimates of the regression coefficient based on Kendall's tau. *J Amer Stat Assoc* 63:1379–1389. <https://doi.org/10.1080/01621459.1968.10480934>
- Sfîcă L, Croitoru AE, Iordache I et al (2017) Synoptic Conditions Generating Heat Waves and Warm Spells in Romania. *Atmosphere* 8:50. <https://doi.org/10.3390/atmos8030050>

- Török I, Croitoru AE, Man TC (2021) Assessing the Impact of Extreme Temperature Conditions on Social Vulnerability. Sustainability 13:8510. <https://doi.org/10.3390/su13158510>
- Vicedo-Cabrera A, Scovronick N, Sera F et al (2021) The burden of heat-related mortality attributable to recent human-induced climate change. Nat Clim Chang 11:492–500. <https://doi.org/10.1038/s41558-021-01058-x>
- Voldoire A, Sanchez-Gomez E, Salas y Méliá D et al (2013) The CNRM-CM5.1 global climate model: description and basic evaluation. Clim Dym 40:2091–2121. <https://doi.org/10.1007/s00382-011-1259-y>
- Wang J, Guan Y, Wu L et al (2021) Changing lengths of the four seasons by global warming. Geophys Res Lett 48:e2020GL09175. <https://doi.org/10.1029/2020GL091753>
- Wilcoxon F (1945) Individual comparisons by ranking methods. Biom Bull 1:80–83
- World Bank (2022) Urban population. <https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?end=2021&locations=EU&start=1960&view=chart&year=2008>. Accessed 9 Aug 2022
- Yiou P, Cattiaux J, Faranda D et al (2020) Analyses of the Northern European Summer Heatwave of 2018. Bull Am Meteorol Soc 101:S35–S40. <https://doi.org/10.1175/BAMS-D-19-0170.1>
- Zhao L, Oppenheimer M, Zhu Q et al (2018) Interactions between urban heat islands and heat waves. Environ Res Lett 13(3):034003. <https://doi.org/10.1088/1748-9326/aa9f73>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Bogdan Antonescu^{1,2,3} · **Dragoş Ene**^{1,4} · **Mihai Boldeanu**^{1,5} · **Simona Andrei**¹ · **Luminiţa Mărmureanu**^{1,6} · **Cristina Marin**^{1,7} · **Răzvan Pîrloagă**^{1,3}

Dragoş Ene
dragos.ene@eratosthenes.org.cy

Mihai Boldeanu
mishuboldeanu@gmail.com

Simona Andrei
simona.andrei@inoe.ro

Luminiţa Mărmureanu
luminita.marmureanu@icas.ro

Cristina Marin
cristinaantoniamarin@gmail.com

Răzvan Pîrloagă
razvan.pirloaga@inoe.ro

² Present address: Future Climate Research, str. Blăjel 13, 031493 Bucharest, Romania

³ Present address: Faculty of Physics, University of Bucharest, Str. Atomîştilor 405, 077125 Măgurele, Romania

⁴ Present address: ERATOSTHENES Centre of Excellence, Limassol, Cyprus

⁵ Present address: University Politehnica of Bucharest, 060042 Bucharest, Romania

⁶ Present address: National Institute for Research and Development in Forestry “Marin Drăcea”, Bvd. Eroilor 128, 077030 Voluntari, Romania

⁷ Present address: Extreme Light Infrastructure-Nuclear Physics, “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Str. Reactorului 30, 077125 Măgurele, Romania

¹ National Institute of Research and Development for Optoelectronics INOE2000, str. Atomîştilor 409, Măgurele 077125, Ilfov, Romania